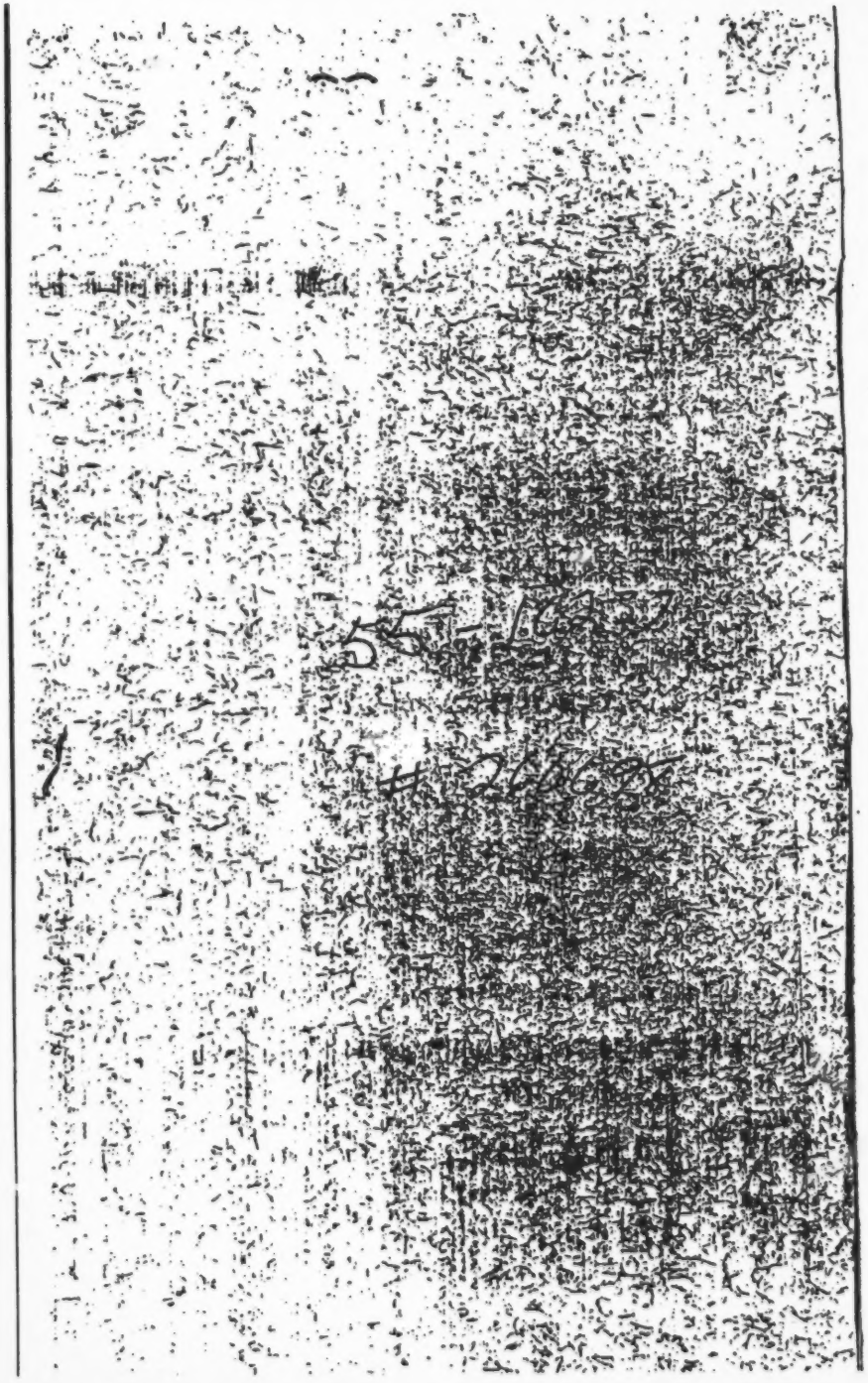

Reprinted from Canadian Journal of Technology, 33: 445–469. 1955

THE OXIDATION, DECOMPOSITION, IGNITION, AND DETONATION OF FUEL VAPORS AND GASES

XXVII. THE HYDROGEN ENGINE[1]

By R. O. King[2] and Mogens Rand[3]

ABSTRACT

Experiments made with hydrogen as the fuel for an Otto cycle engine show that optimum performance in terms of power and economy is limited only by preignition arising from the temperatures attained by the ceramic core of the spark plug or by the exhaust valve, or from nuclei formed by pyrolysis of lubricating oil vapor. On reduction of the magnitude of these igniting effects it became possible to operate the engine with speeds rising to 1800 r.p.m. and the compression ratio fixed at 12:1. A value of 146 p.s.i. for I.M.E.P. with an indicated thermal efficiency of 37% was obtained when the maximum power mixture strength was used. A value of 90 p.s.i. was obtained for I.M.E.P. with an indicated thermal efficiency of 47% with a mixture 56% weak. These values exceed, by a wide margin, any recorded in the literature of the subject.

INTRODUCTION

Results in conformity with the nuclear theory of ignition, as stated in Part IV (7), were obtained when hydrogen was used as the fuel for experiments with a C.F.R. knock rating engine (Part V (12)). These experiments were carried out at the standard knock rating speed of 900 r.p.m. and with compression ratios rising to 10:1. Ignition otherwise than by the electric spark did not occur unless finely divided carbon had been allowed to accumulate in the combustion chamber. It was found later that the carbon was a product of the pyrolysis of lubricating oil *vapor*. A similar igniting effect occurred when charcoal dust was added to the hydrogen–air mixture before it entered the combustion chamber and when in subsequent experiments the laboratory atmosphere was impregnated to an unusual degree with concrete dust (11). This was of especial interest in that the nuclei were not combustible. A significant feature of the experiments was the occurrence of some degree of preignition on increase of the temperature of the jacket coolant from 140° to 212°F. This effect according to the nuclear theory of ignition would be due to a surface in the combustion chamber having attained an igniting temperature or to nuclear ignition arising from an increase in the rate of vaporization of lubricating oil. The surfaces that would be expected to attain an igniting temperature were those of the exhaust valve, and the ceramic core of the spark plug or of its central electrode. The most effective way of raising the temperature of these indirectly cooled surfaces would have been to increase the heat load by increasing engine speed but the unbalanced C.F.R. knock rating engine

[1]*Manuscript received May 31, 1955.*
Contribution from Defence Research Board, Ottawa, Canada, in association with the Department of Mechanical Engineering, University of Toronto, Toronto, Ontario.
[2]*Scientific Officer-in-Charge, Combustion Research, Defence Research Board, Ottawa, Canada, and Special Lecturer, Department of Mechanical Engineering, University of Toronto.*
[3]*Principal Scientific Officer, Defence Research Board.*

106-04361/

was not suitable for operation at speeds higher than 900 r.p.m. The engine experiments were therefore discontinued until a C.F.R.-F4 engine, balanced for high speed operation, became available for the new series of experiments described in this Part.

Experiments with combustion tubes of materials similar to those in the combustion chamber of the engine were however initiated in order to determine the wall temperature required for the ignition of hydrogen–air mixtures passing through them and are described in Part XXVI (10).

EXPERIMENTAL ARRANGEMENTS AND METHODS, PRESENTATION OF RESULTS

The Engine

The C.F.R.-F4 engine, bore 3½ in. stroke 4½ in., is fitted with balancing pistons in the crank case, as required for high speed running. The cast iron piston is fitted with an oil scraper ring and three pressure rings. The engine was direct connected to a d-c. generator arranged as a swinging field dynamometer for the measurement of B.H.P. directly and of I.H.P. by the motoring method. Provision was made for the measurement of compression ratios varying from 4 to 20:1.

Camshafts which provided suitable valve timing for speed ranges of 900 to 1200 r.p.m. and 1200 to 1500 r.p.m. were available. They will be described respectively as low and high speed camshafts. The valve timing and lift are given in the appendix to this Part.

Cylinders with holes for three spark plugs in the wall and one in the head were available. One was fitted with a sodium cooled exhaust valve, and others with the C.F.R. standard uncooled valve of silchrome steel. The types of the cooled and uncooled valves are illustrated by Fig. 15 of the appendix. A plain or a shrouded inlet valve could be used in either cylinder.

Exhaust Valve Surface State

The surface state of the face of the exhaust valve varies with time of use and this was found to have an appreciable effect on the temperature required for the ignition of other than weak hydrogen–air mixtures. Exhaust valves with two varieties of surface state were used, namely *clean* and *aged*.

A valve cleaned with abrasive material and then washed with alcohol before a set of experiments was begun is described as *clean* although it ceases to remain in that condition to an extent depending on the time required to complete a set. A running time of from three to four hours is generally required.

An *aged* valve is one that has been used for many sets of experiments and cleaned only by washing with alcohol, before a set of experiments is begun.

The Ignition System

The designs of spark plugs used for the experiments are illustrated by Fig. 14 of the appendix. Champion C.F.R.-8 was until recently the standard spark plug for use with the A.S.T.M.-C.F.R. method of knock rating. It is a "hot" variety, near the top of the commercial heat scale. Spark plugs K.L.G. 100 and Champion R 2-S were used as cool varieties.

The coil ignition supplied as standard had been found to be ineffective with hydrogen–air mixtures at a C.R. of 10.0, unless the spark gap were reduced to 0.012 in. A special Auto-Lite ignition system was used for experiments made subsequently with hydrogen and other gases and it was then possible to increase the spark gap to 0.025 in. if necessary. The system is described in the appendix to Part XIII (9).

Temperature Control

It was found in the course of preliminary experiments that as the heat load carried by the engine was raised, by increasing speed for example, it became necessary to control the temperatures of the air and hydrogen supplied to the engine if repeatable results were to be obtained. The temperature of the air drawn from the laboratory atmosphere was subject to variations of approximately 40°F. The method used for maintaining the supply of air and hydrogen at a nearly constant temperature of 65°F. is described in the appendix to this Part.

Water was used as the jacket coolant and temperatures lower than 212°F. were controlled automatically by the thermostatic method described in Part XIII (9, pp. 152–153). The flow of water through the cylinder jacket could be controlled by this method to ensure that the temperature at the outlet was never more than 5°F. higher than that at the inlet.

The lubricating oil in the crank case sump was maintained at 140°F. by an exterior electric heater with manual control. Oil pressures maintained at speeds of 900, 1200, 1500, and 1800 r.p.m. were 18, 21, 23, and 25 p.s.i. respectively.

The Hydrogen Supply

Electrolytic hydrogen as supplied by the Canadian Liquid Air Company, Toronto, compressed to 2000 p.s.i. in steel cylinders was used for the experiments. The hydrogen was reputed to be 99.95% pure and as compressed was nearly dry, the dew point being below minus 100°F. The lower calorific value as used for calculations of thermal efficiency was taken as 274.5 B.T.U. per cu. ft., at 60°F. and 30 in. Hg. The method used for the measurement of the rate of hydrogen supply to the engine is described in the appendix to this Part.

The Lubricating Oil

A separate series of experiments with lubricating oils indicated that the least amount of residue remained in the combustion chamber after Ucon had been used. This is a synthetic lubricant made by the Carbide and Chemicals Corporation with a base composed of polyalkylene glycols and derivatives. The grade selected for the experiments is described as L.G. 300 X, which indicates that it is water insoluble, has a viscosity of 300 Saybolt universal seconds, and is oxidation inhibited but without additives. According to A.S.T.M. tests, the viscosity index is 142, ash less than 0.01%, carbon residue also less than 0.01%, and water less than 0.25%. The viscosity is close to S.A.E. 30 at 210°F. and the same as S.A.E. 20 at 130°F.

Methods of Experiment

The engine was always prepared for a particular set of experiments by being dismantled for a top overhaul. The cylinder, piston, and rings were then washed with acetone and alcohol. The valves were inspected and hand lapped into their seats if signs of leakage were detected. On conclusion of the set it was verified, by measurement of compression pressure before the engine had cooled, that piston sealing had not deteriorated.

The lubricating oil and the jacket cooling water were heated electrically to working temperatures before a set of experiments was begun. The engine was then started on a hydrogen–air mixture 50% weak and run for at least 30 min. The mixture was then reduced to the leanest on which the speed selected for the first experiment could be maintained. This was always the lowest of the speeds to be used for a set of experiments. The engine was then run for 15 min. before a determination of the optimum spark timing.

Hydrogen burns with high velocity in mixtures with air approaching and exceeding the correct value and relatively slowly when in small concentration in air, and the ignition timing required for maximum power output when a particular mixture strength and engine speed was used can be determined with accuracy, solely by a series of lower measurements. Brake horsepower was measured accordingly for a series of ignition timings giving rising and falling values for power output and the optimum timing was then obtained from a plot of results, as described in Part XII (8, pp. 438–439).

Presentation of Experimental Results

Experiments were carried out at engine speeds rising to 1800 r.p.m. and with compression ratios of 10 and 12:1. Comprehensive performance data are given by graphs plotted on a mixture strength base as used for experiments with liquid fuels. A "correct" mixture is 100% stoichiometric. The percentage stoichiometric diminishes or increases as the mixture is weakened or enriched. Thus for example a mixture 20% weak is 80% of stoichiometric and one 20% rich is 120% of stoichiometric.

The terms Compression Ratio, Mixture Strength, Indicated Thermal Efficiency, and Indicated Mean Effective Pressure are, when convenient, abbreviated to C.R., M.S., I.T.E., and I.M.E.P. respectively. Values of C.R. are given as single numbers. A stoichiometric mixture is described as "correct" in the text; the abbreviation C.C.M. is used on the graphs. It is to be understood that numerical values given on graphs for I.M.E.P. and Engine Speed are in pounds per square inch (p.s.i.) and revolutions per minute (r.p.m.) respectively.

I. THE IGNITING EFFECT OF THE CERAMIC CORE OF A SPARK PLUG

Preliminary Experiments

The operating conditions were similar to those in which some degree of preignition occurred in the course of the experiments described in Part V (12) when a correct hydrogen–air mixture was used at a C.R. of 10, with the

jacket coolant at 212°F. and the mixture supplied at room temperature. A C.F.R.-8 spark plug which is a "hot" variety was used, the exhaust valve was of silchrome steel, uncooled, and the inlet valve was of the shrouded type which provided a swirl in the entering mixture. Thus the conditions were essentially those used for the knock rating of fuels by the C.F.R.-A.S.T.M. motor method.

The experiments were carried out with the C.R. fixed at 10, with engine speeds of 600, 900, 1200, and 1500 r.p.m. while mixtures were varied from very weak to extremely rich. The results obtained for the relation between I.H.P. and M.S. are given by the graphs of Fig. 1.

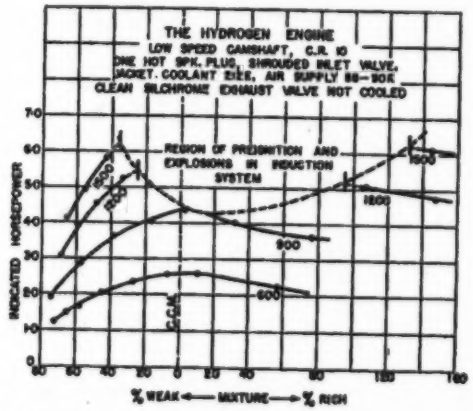

FIG. 1. Mixture strengths over which premature ignition occurs when engines speeds exceed 900 r.p.m. and a C.F.R.-8 spark plug, a hot variety, is used in the standard position.

It will be seen by reference to the graphs that at 600 r.p.m. a maximum value of 2.6 was obtained for I.H.P. when the mixture was 10% rich. There was no preignition. When however the heat load was increased by raising the speed to 900 r.p.m. and I.H.P. attained a maximum of 4.3, there was some degree of preignition but not enough to interrupt the experiment. This result was similar to that obtained in similar conditions as described in Part V (12). Then when the heat load was further increased by raising the speed to 1200 and then to 1500 r.p.m. the range of M.S. over which running was impossible, because of backfiring into the induction system, increased as shown by the relevant graphs. Thus at 1500 r.p.m. backfiring occurred over the mixture range 40% weak to 140% rich.

Ignition by a Hot Spark Plug without a Central Electrode

Preignition is frequently attributed to the central electrode of the spark plug becoming overheated. Pye (15, p. 91), for example, mentions only the

central electrode and scraps of incandescent carbon; Hundere and Bert (6, p. 553), fragments *detached* from the ceramic core. The experiments described in Part XXVI (10) indicated that preignition would preferably be initiated by the surface of the ceramic core of the spark plug even if its temperature were not higher than that of other surfaces in the combustion chamber.

Experiments were carried out accordingly in the operating conditions used for the preliminary experiments but with the mixture fired by a cool variety of spark plug, a K.L.G.-100, in the standard position while a standard but unfired hot variety, a C.F.R.-8, was in the No. 2 position. The central electrode of this plug had been cut off. The standard and the No. 2 positions are shown by Fig. 2. It will be seen by reference to the figure that the swirl due to the

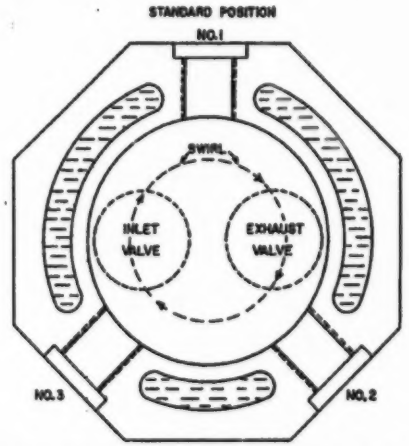

FIG. 2. Location of spark plug holes in wall of the combustion chamber and the mixture swirl due to the use of the C.F.R. shrouded inlet valve.

shrouded inlet valve directs the relatively cool entering mixture over the spark plug in the standard position and that it then passes over the hot exhaust valve before arriving at the unfired plug in the No. 2 position.

The experimental results obtained for the relation between I.H.P. and M.S. with speeds of 600, 900, 1200, and 1500 r.p.m. are given by the graphs of Fig. 3. It was just possible to use the maximum power mixture strength without the occurrence of preignition at the low speed of 600 r.p.m., the corresponding maximum I.H.P. being 2.6. Then on raising the speed to 900 r.p.m. preignition accompanied by backfiring occurred with mixtures ranging from 10% weak to 67% rich and the range of mixture strength over which running was impossible increased as speed and the corresponding heat load were further increased, as illustrated by the graphs of the figure.

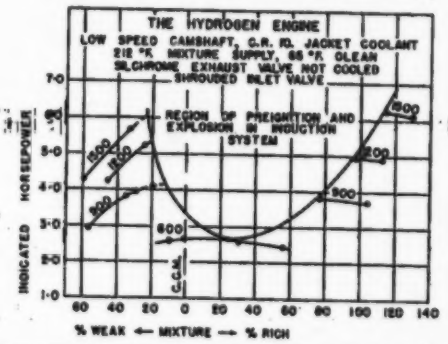

FIG. 3. Mixture strengths over which premature ignition occurs at engine speeds exceeding 600 r.p.m. when an unfired hot spark plug without projecting central electrode is in No. 2 position and ignition is by a cool spark plug in the standard position.

II. THE LIMITATION OF POWER AND ECONOMY BY THE ONSET OF PREIGNITION DUE TO THE ATTAINMENT OF AN IGNITING TEMPERATURE BY THE CERAMIC CORE OF THE SPARK PLUG

The experiments described in Section I were carried out at a C.R. of 10 and in the absence of an accumulation of finely divided carbon in the combustion chamber. The maximum power attainable was limited by preignition arising from the ceramic core of the C.F.R.-8 spark plug having attained an igniting temperature in respect of the hydrogen–air mixture. Moreover it was shown by the experiments with combustion tubes (Part XXVI (10)) that a correct mixture would be ignited by the exhaust valve if it attained a temperature of approximately 1100°F. It was decided accordingly to use a sodium cooled valve for further experiments and to maintain the jacket coolant at 100°F. and the entering mixture at 65°F. The shrouded inlet valve was replaced by a plain type although this led to an increase in volumetric efficiency and consequently to an increase in heat load. The volumetric efficiency at high speeds was however restricted to some extent by the continued use of the low speed camshaft. The object of the changes mentioned was to ensure that preignition, when it occurred, was due solely to the temperature attained by the ceramic core of the spark plug. Experiments were carried out at a C.R. of 10 and with speeds of 900, 1200, 1500, and 1800 r.p.m. when a hot spark plug was used and repeated after a change to a cool variety of spark plug.

Hot Spark Plug Experiments

A Champion C.F.R.-8 was used as a hot plug. The relation between I.H.P. and the values of M.S. that could be used before the experiment was interrupted by the occurrence of preignition and backfiring is given by the *A* graphs of Fig. 4, for the four engine speeds. Backfiring began on increasing M.S. to the values shown by the short vertical lines of the graphs. The mixture was then 42% weak at speeds of 1500 and 1800 and 38% weak at 900 and 1200. A value

of 40% weak, taken irrespective of engine speed, would be within experimental accuracy. Preignition and backfiring did not occur when extremely rich mixtures were used. The values then obtained for I.H.P. are not given by the graphs. The small ranges of M.S. usable in the conditions of the experiments included the weak value for which indicated thermal efficiency was a maximum. Relevant data are tabulated below.

TABLE I

MIXTURE STRENGTH FOR MAXIMUM I.T.E., 60% WEAK
ONE HOT SPARK PLUG, LOW SPEED CAMSHAFT, C.R. 10.0

Speed	Opt. spk. Advance	I.M.E.P.	I.T.E.%
1800	30°	80	43.0
1500	32°	81	43.5
1200	32°	81	43.0
900	32°	80	41.5

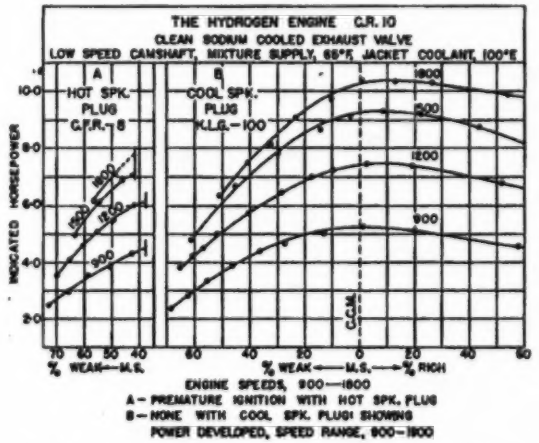

FIG. 4. Graphs *A* and *B* illustrate the effect of changing from a hot to a cool variety of spark plug; other running conditions having remained unchanged.

Cool Spark Plug Experiments

A K.L.G. 100 was used as a cool plug. The relation between I.H.P. and M.S. then obtained without otherwise changing conditions of experiment is given by the *B* graphs of Fig. 4. They show that a remarkable effect, which prevented premature ignition, had been obtained. Thus referring to the figure it will be

seen that hydrogen–air mixtures ranging from 70% weak to 80% rich were used at speeds ranging from 900 to 1800.

The values obtained for I.T.E. and I.M.E.P. when the M.S. was used for maximum power and optimum spark timing are given, in Table II, below. Maximum power was always obtained when using a mixture 5% rich. The values for I.T.E. and the corresponding values of I.M.E.P. obtained when using the M.S. for maximum I.T.E. are given in Table III.

TABLE II

MIXTURE STRENGTH FOR MAXIMUM POWER, 5% RICH
ONE COOL SPARK PLUG, LOW SPEED CAMSHAFT, C.R. 10

Speed, r.p.m.	% Vol. eff.	Spk. timing	I.H.P.	I.M.E.P.	I.T.E.
1800	77	1° adv.	10.4	123	36
1500	84	t.d.c.	9.3	132	35
1200	86	1° ret'd	7.6	134	35
900	85	1° ret'd	5.4	126	33

TABLE III

MIXTURE STRENGTH FOR MAXIMUM THERMAL EFFICIENCY, 55% WEAK
ONE COOL SPARK PLUG, LOW SPEED CAMSHAFT, C.R. 10

Speed, r.p.m.	% Vol. eff.	Spk. adv.	I.H.P.	I.M.E.P.	I.T.E.
1800	75	35°	6.1	75	43.6
1500	85	26°	6.0	85	44.0
1200	91	28°	4.9	87	42.4
900	91	22°	3.6	85	42.0

It is shown by the data of Tables II and III that a maximum value of 134 was obtained for I.M.E.P. with a speed of 1200 and the somewhat lower value of 132 on increasing speed to 1500. A maximum of 42.4% was obtained for I.T.E. with a speed of 1200 and of 44% on increasing the speed to 1500. The I.H.P. obtained with the maximum lower mixture increased from 4.9 to 6.0 on increasing the speed from 1200 to 1500 but an increase to 6.1 only was obtained on further increasing speed to 1800 and the I.M.E.P. decreased from 132 to 123.

It is evident that the valve timing provided by the low speed camshaft was suitable for use at speeds of from 1200 to 1500 but not for a speed of 1800. Comprehensive performance data were obtained for the four speeds used for the experiments and with mixtures ranging from 66% weak to 60% rich. The data are given by the graphs of Fig. 5 for a speed of 1500 only.

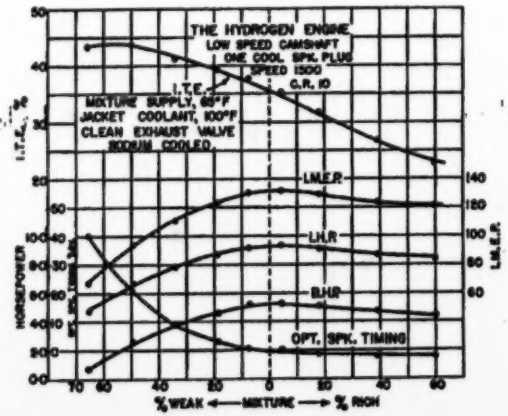

FIG. 5. Performance data, mixtures 66% weak to 60% rich, obtained when ignition is by a cool spark plug, speed 1500 r.p.m. and C.R. 10:1.

III. THE MEAN TEMPERATURES ATTAINED BY HOT AND COOL SPARK PLUG CORES, AN UNCOOLED EXHAUST VALVE, AND THE EXHAUST GAS AS AFFECTED BY MIXTURE STRENGTH

The experiments were carried out with an engine speed of 1200 r.p.m., a C.R. of 10, temperatures of jacket coolant and mixture supply 100° and 65°F. respectively. The experimental results are given by the graphs of Fig. 6.

The C.F.R.-8 Spark Plug

The spark plug with a thermocouple in the central electrode near the tip of the ceramic core was supplied by the Champion Spark Plug Company. Thus the temperature at that position could be measured while the spark plug, placed in the standard position, was used to fire the hydrogen–air mixture. The temperatures attained as M.S. was increased from 70% weak are given by the *A* graph of the figure. Preignition occurred on increasing the M.S. to 33% weak. A temperature of 1150°F. had then been attained at the position of the thermocouple.

The Uncooled Exhaust Valve

The valve was of silchrome steel, supplied as standard for the C.F.R.-A.S.T.M. motor method of knock rating. It was obtained with the stem drilled for a thermocouple to be fitted in a manner suitable for the measurement of the temperature of the exposed surface. The temperatures thus measured while ignition was provided by a cool spark plug, a K.L.G. 100, in the standard position, are given by the *B* graph of the figure. It will be seen that the temperature of the exhaust valve rose from 590° to a maximum of 1150°F. as M.S. was increased from 66% weak to 5% rich. There was no preignition.

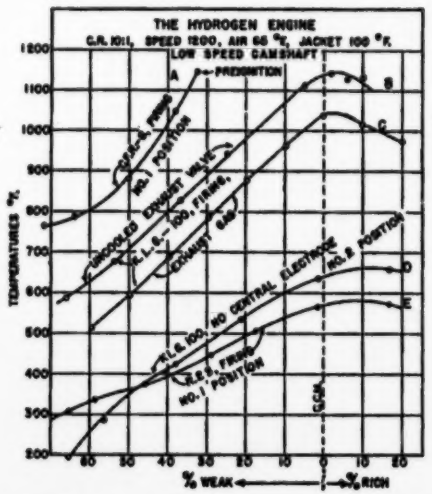

FIG. 6. Mixture strength and the corresponding temperatures of an uncooled exhaust valve, the exhaust gas, and hot and cool spark plugs.

The Exhaust Gas

The temperature was measured by using a bare thermocouple placed in the exhaust system approximately 3 in. from the valve. The temperatures thus measured, as M.S. was increased from 60% weak to 20% rich, are given by the *C* graph of the figure. They were measured at the same time as those of the uncooled exhaust valve. It will be noted that the temperature of the uncooled exhaust valve was always higher than that of the exhaust gas. The temperature of a sodium cooled valve in an air cooled cylinder was always lower than that of the exhaust gas, according to experiments by Sanders, Wilstead, and Mulcahy (17).

The Cool Spark Plugs, R2-S and K.L.G.-100

An R2-S spark plug with a thermocouple in the central electrode near the top of the ceramic core was placed in the standard position and used for firing the mixture. A K.L.G.-100 was prepared for the experiments by removing the central electrode and replacing it by a thermocouple cemented in at about 1/8 in. from the tip of the ceramic core. This plug was placed in the No. 2 position. The inlet valve was of the plain type, thus there was no swirl to influence the relative temperatures attained by the spark plugs. The K.L.G. plug in the No. 2 position was however closer to the exhaust valve than the champion plug in the standard positions. The temperatures, as measured while M.S. was increased from 70% weak to 20% rich, are given by graphs *D* and *E* of the figure. It will be seen that the temperatures attained by the two

plugs did not differ to a significant extent, allowing for their relative positions, and that the maximum temperature of 670°F., which was attained with a mixture 10% rich by the K.L.G.-100 plug, is far below that required for the ignition of any hydrogen–air mixture.

IV. THE LIMITATION OF POWER AND THERMAL EFFICIENCY BY THE ONSET OF PREIGNITION DUE TO THE EXHAUST VALVE HAVING ATTAINED AN IGNITING TEMPERATURE

The experiments described in Sections II and III demonstrated that preignition due to the ceramic core of the spark or to its central electrode did not occur when a cool type of spark plug was used. It was shown however, by the *B* graph of Fig. 6, that the temperature attained by the exhaust valve approached the value required for the ignition of a correct hydrogen–air mixture when the engine speed was 1200 r.p.m. and the C.R. 10:1. It appeared therefore that preignition by the exhaust valve might become a limiting factor in respect of power and thermal efficiency on raising the heat load.

Experiments were therefore carried out in the operating conditions used for those described in Sections II and III, except that volumetric efficiency and the consequent heat load were increased by using a "high speed" camshaft. There was then a corresponding increase in the temperature of the exhaust valve and a further increase due to the valve lift being increased from 0.238 in. to 0.312 in. and to the time the valve was off its cooling seat being increased from 145° to 155° of crank revolution. The values for I.H.P. obtained with mixtures ranging from 70% weak to 60% rich are given by the graphs of Fig. 7. The I.H.P. attained a maximum of 11.0 with a speed of 1800 r.p.m. as compared with the value of 10.4 obtained when using the low speed camshaft,

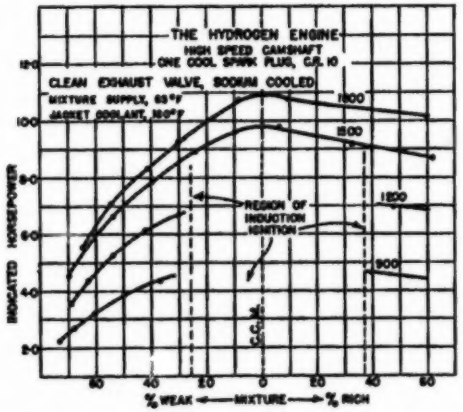

FIG. 7. Premature ignition at speeds lower than 1500 r.p.m. as obtained when changing to the high speed camshaft, other running conditions remaining unchanged.

Fig. 4. The especially noteworthy feature of the experiments was that preignition and backfiring into the induction system occurred when speed was *reduced*.

An explanation was provided by the results of the experiments with steel combustion tubes, Part XXVI (10). It was found in these experiments that the igniting effect of a clean stainless steel surface was reduced if it was aged by exposure at high temperatures to hydrogen–air mixtures for the time required for the formation of an adherent layer of oxide. Moreover it was shown that the difference in the igniting effects increased as time of exposure to hydrogen–air mixtures was increased. Thus it would be expected that in the engine an exhaust valve with a clean surface would ignite a hydrogen–air mixture at a lower temperature than would be required by one with an aged surface and that the difference in the igniting effects would increase on decreasing the engine speed.

The surface of the exhaust valve had always been cleaned with abrasive material for the experiments described earlier in this Part but in view of the results of the experiments with stainless steel combustion tubes the clean exhaust valve was replaced by a similar sodium cooled valve which had been put aside after having been used for a long period during which a coating of oxide had formed. The valve is described accordingly as "aged".

The engine then ran at speeds ranging from 900 to 1800 r.p.m. with an entire absence of preignition. No alteration other than the change of exhaust valves had been made in the operating conditions. The values obtained for I.H.P. when mixtures ranging from 70% weak to 70% rich were used are given by the graphs of Fig. 8. The experiments were of a preliminary nature made to verify that preignition would be avoided by using an aged instead of an initially clean exhaust valve.

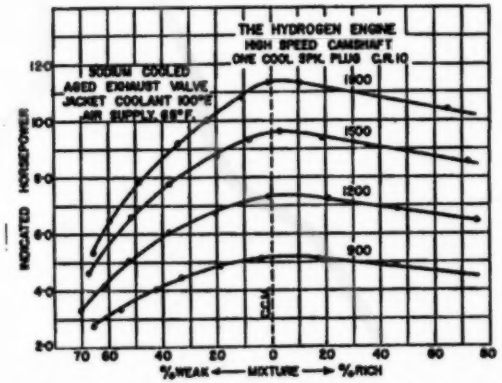

FIG. 8. Graphs showing the absence of low speed premature ignition when the exhaust valve was aged.

Performance Data for Six Engine Speeds

Further experiments were carried out to obtain complete performance data when the aged exhaust valve was used with speeds of 1100 and 1300 r.p.m. in addition to the speeds of 900, 1200, 1500, and 1800 r.p.m., while mixtures were varied from 70% weak to 70% rich. The data obtained when the mixtures required for maximum I.H.P. and maximum I.T.E. were used are tabulated in Tables IV and V, respectively.

TABLE IV

MIXTURE STRENGTH FOR MAXIMUM POWER; AGED EXHAUST VALVE
HIGH SPEED CAMSHAFT, ONE COOL SPARK PLUG, C.R. 10

Speed	% Vol. eff.	Spk. timing	M.S.	I.H.P.	I.M.E.P.	I.T.E.%
1800	81.1	2° adv.	5% rich	11.40	135	36.5
1500	89.6	t.d.c.	6% rich	9.65	139	35.0
1300	89.0	t.d.c.	7% rich	8.05	132	34.5
1200	90.6	t.d.c.	6% rich	7.40	131	34.0
1100	87.8	t.d.c.	6% rich	6.60	128	33.5
900	84.5	2° retard	5% rich	5.25	122	33.0

TABLE V

MIXTURE STRENGTH FOR MAXIMUM INDICATED THERMAL EFFICIENCY, 55% WEAK;
AGED EXHAUST VALVE
HIGH SPEED CAMSHAFT, ONE COOL SPARK PLUG, C.R. 10

Speed	% Vol. eff.	Spk. adv.	I.H.P.	I.M.E.P.	I.T.E.%
1800	83	24°	7.0	83	44.4
1500	87	27°	6.1	87	43.2
1300	84	30°	5.1	84	42.0
1200	84	31°	4.8	84	41.5
1100	82	30°	4.2	82	41.5
900	80	30°	3.3	80	40.2

It will be seen by reference to Table IV that I.H.P. was 11.4 at 1800 r.p.m., as compared with 10.4 H.P. obtained when the low speed camshaft was used, see Table II. The maximum values for I.M.E.P. and volumetric efficiency were obtained at 1500, indicating that the valve timing provided by the high speed camshaft was most suitable for that engine speed provided that preignition was avoided by using an aged exhaust valve. The I.M.E.P. was then 139 as compared with a value of 132 p.s.i. obtained when the low speed camshaft and a speed of 1500 was used, and 134 when the speed was 1200 r.p.m. It may be concluded that in so far as I.M.E.P. is concerned, the valve timing provided by the low speed camshaft is most suitable for an engine speed of 1200 and that provided by the high speed camshaft is best for an engine speed of 1500 r.p.m.

The maximum values for I.T.E. were always obtained when the mixtures were 55% weak, when either the low or the high speed camshaft was used.

The values obtained with the low speed camshaft, Table III, increased from 42% at a speed of 900 to attain a maximum of 44% at 1500 r.p.m. and a lower value of 43.6% at 1800 r.p.m. On the other hand the values obtained when the high speed camshaft was used increased with fair regularity from a low of 40.2% at 900 to a maximum of 44.4% at 1800 r.p.m., Table V. Performance data for mixtures ranging from 70% weak to 80% rich are given by the graphs of Fig. 9 for the engine speed of 1500 at which a maximum of 139 was obtained for I.M.E.P.

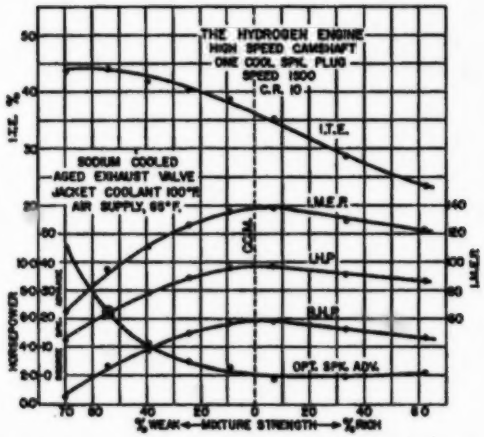

FIG. 9. Performance data, mixtures 70% weak to 64% rich, obtained when using the high speed camshaft and the aged exhaust valve. Speed 1500 r.p.m. C.R. 10:1.

Indicator Diagrams

The indicator diagrams, Fig. 10, were taken when a Draper-Li pressure pickup was used. The pressure scale is linear and maximum values in pounds per square inch are given by the calibration marks on the diagrams. The diagrams were taken when a C.R. of 10 was used and when, under the operating conditions used, the performance data given in Tables IV and V were obtained, at an engine speed of 1500 r.p.m.

The pressure waves started by the spark are most pronounced, when with mixtures nearly correct the pressure rise due to combustion began immediately after its passage, diagrams *A* and *B*. Spark timing is shown on the diagrams by small rather faint blips fed into the electronic circuit. These are marked by arrows. Similar blips marked by short vertical lines were fed into the circuit at t.d.c. and at intervals of 10° for 30° before and after.

Spark timing was always adjusted to obtain maximum power output and it will be noted that maximum combustion pressure then occurred at approxi-

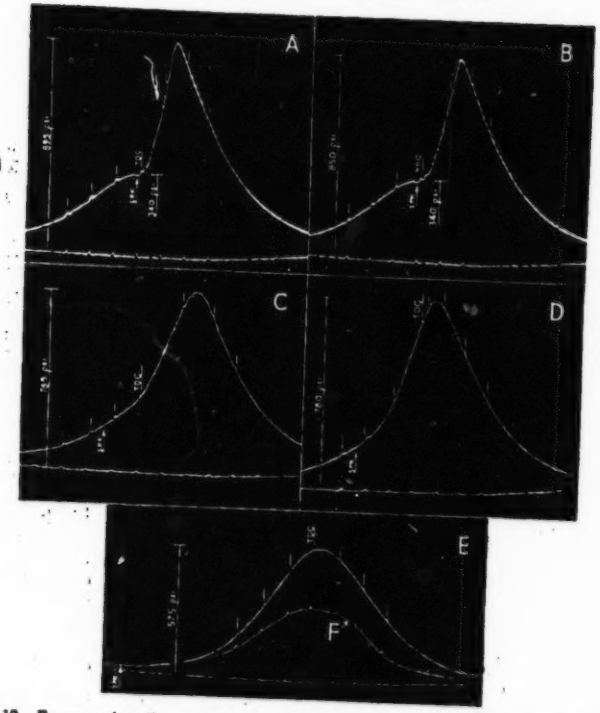

FIG. 10. Pressure-time diagrams taken with a Draper-Li pressure pickup. C.R. 10:1 speed 1500 r.p.m.
A, M.S. 3% rich, spk. 1° retard. *B*, M.S. 8% weak, spk. 1° adv.
C, M.S. 34% weak, spk. 14° adv. *D*, M.S. 50% weak, spk. 25° adv.
E, M.S. 80% weak, spk. 75° adv. *F*, air only.

mately 15° after t.d.c. when the mixture was nearly correct, diagrams *A* and *B*, but at approximately 5° after t.d.c. when mixtures 34, 50, and 80% weak were used, diagrams *C*, *D*, and *E*.

The power developed with a mixture 80% weak was insufficient to overcome friction and pumping losses and the speed of 1500 r.p.m. was maintained by partial motoring of the engine. Diagram *F*, shown below diagram *E*, was taken when air only was supplied to the engine. The pressures shown accordingly can be used for estimating the approximate combustion pressures obtained when mixtures with hydrogen were used.

The diagrams show that if lubricating oil passed into the combustion chamber at the minimum rate practicable, the rate of burning of a hydrogen–air mixture 5% rich or 8% weak was such that its combustion required a time

represented by nearly 15° of crank revolution and that *autoignition did not occur even when the compression ratio was* 10:1.

V. OPERATION OF THE ENGINE AT 12:1 COMPRESSION RATIO

The controllable operating conditions were as had been used at a C.R. of 10, as described in Section IV, except that the temperature of the jacket coolant was reduced from 100° to 65°F. An unavoidable change in conditions occurred on raising the C.R. to 12:1, in that the top piston ring then lost its bearing on the cylinder wall at the three spark plug holes. Moreover a larger pocket into which lubricating oil could leak past the piston was formed between the end of the spark plug and the top piston ring than between the ends of the two blank plugs and the piston ring.

The operation of the engine at a C.R. of 12 and a speed of 1800 r.p.m. in the conditions described was accompanied by some degree of preignition which occurred occasionally only and did not lead to backfiring. When however volumetric efficiency was increased by reducing the speed to 1500 r.p.m., preignition occurred occasionally with a mixture 5% rich, frequently with one 30% rich, and developed into backfiring with a mixture 80% rich.

The engine was then dismantled for inspection and cleaning of the combustion chamber. Patches of soot, easily wiped off, were found on the piston crown adjacent to the three spark plug holes. The patch adjacent to the spark plug hole was larger than those adjacent to the two holes occupied by blank plugs. Similar patches of soot were not found when the engine was dismantled after running at a C.R. of 10.

Method of Avoiding Preignition by Lubricating Oil Soot and the Consequent Improvement in Engine Performance

The extent of the deposits of soot on surfaces in the combustion chamber was found to depend on the time of running required for the accumulation of a quantity of lubricating oil in the pockets provided by the spark plug holes. Thus starting with a weak mixture and taking the observations required for performance data as rapidly as possible, it was found that preignition did not occur until a mixture richer than correct was used. When a mixture 10% weak was again used and the engine run for 10 to 15 min., the excess soot on the piston crown burned off and observations for performance data for the richer mixture without interruption by preignition were obtained. With this procedure, performance data were obtained for mixtures ranging from 70% weak to 80% rich and, in the absence of preignition, higher values for power and thermal efficiency were obtained than when experiments had been interrupted by preignition and backfiring.

Values for I.H.P. obtained at speeds of 1200, 1500, and 1800 r.p.m. and with hydrogen–air mixtures ranging from 70% weak to 80% rich are given by the graphs of Fig. 11.

Values for I.H.P., B.H.P., I.M.E.P., I.T.E., and opt. spark timing are given for a speed of 1500 with mixtures ranging from 70% weak to 80% rich, by the graphs of Fig. 12.

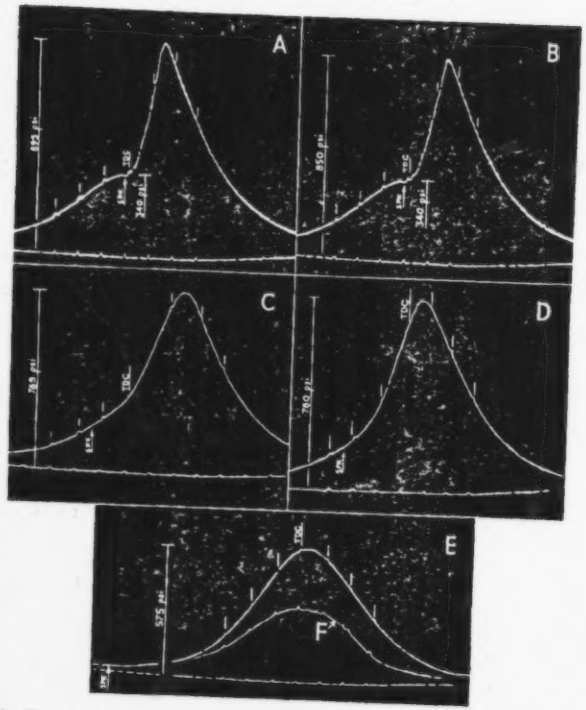

FIG. 10. Pressure–time diagrams taken with a Draper-Li pressure pickup. C.R. 10:1 speed 1500 r.p.m.
A, M.S. 3% rich, spk. 1° retard. *B*, M.S. 8% weak, spk. 1° adv.
C, M.S. 34% weak, spk. 14° adv. *D*, M.S. 50% weak, spk. 25° adv.
E, M.S. 80% weak, spk. 75° adv. *F*, air only.

mately 15° after t.d.c. when the mixture was nearly correct, diagrams *A* and *B*, but at approximately 5° after t.d.c. when mixtures 34, 50, and 80% weak were used, diagrams *C*, *D*, and *E*.

The power developed with a mixture 80% weak was insufficient to overcome friction and pumping losses and the speed of 1500 r.p.m. was maintained by partial motoring of the engine. Diagram *F*, shown below diagram *E*, was taken when air only was supplied to the engine. The pressures shown accordingly can be used for estimating the approximate combustion pressures obtained when mixtures with hydrogen were used.

The diagrams show that if lubricating oil passed into the combustion chamber at the minimum rate practicable, the rate of burning of a hydrogen–air mixture 5% rich or 8% weak was such that its combustion required a time

represented by nearly 15° of crank revolution and that *autoignition did not occur even when the compression ratio was* 10:1.

V. OPERATION OF THE ENGINE AT 12:1 COMPRESSION RATIO

The controllable operating conditions were as had been used at a C.R. of 10, as described in Section IV, except that the temperature of the jacket coolant was reduced from 100° to 65°F. An unavoidable change in conditions occurred on raising the C.R. to 12:1, in that the top piston ring then lost its bearing on the cylinder wall at the three spark plug holes. Moreover a larger pocket into which lubricating oil could leak past the piston was formed between the end of the spark plug and the top piston ring than between the ends of the two blank plugs and the piston ring.

The operation of the engine at a C.R. of 12 and a speed of 1800 r.p.m. in the conditions described was accompanied by some degree of preignition which occurred occasionally only and did not lead to backfiring. When however volumetric efficiency was increased by reducing the speed to 1500 r.p.m., preignition occurred occasionally with a mixture 5% rich, frequently with one 30% rich, and developed into backfiring with a mixture 80% rich.

The engine was then dismantled for inspection and cleaning of the combustion chamber. Patches of soot, easily wiped off, were found on the piston crown adjacent to the three spark plug holes. The patch adjacent to the spark plug hole was larger than those adjacent to the two holes occupied by blank plugs. Similar patches of soot were not found when the engine was dismantled after running at a C.R. of 10.

Method of Avoiding Preignition by Lubricating Oil Soot and the Consequent Improvement in Engine Performance

The extent of the deposits of soot on surfaces in the combustion chamber was found to depend on the time of running required for the accumulation of a quantity of lubricating oil in the pockets provided by the spark plug holes. Thus starting with a weak mixture and taking the observations required for performance data as rapidly as possible, it was found that preignition did not occur until a mixture richer than correct was used. When a mixture 10% weak was again used and the engine run for 10 to 15 min., the excess soot on the piston crown burned off and observations for performance data for the richer mixture without interruption by preignition were obtained. With this procedure, performance data were obtained for mixtures ranging from 70% weak to 80% rich and, in the absence of preignition, higher values for power and thermal efficiency were obtained than when experiments had been interrupted by preignition and backfiring.

Values for I.H.P. obtained at speeds of 1200, 1500, and 1800 r.p.m. and with hydrogen–air mixtures ranging from 70% weak to 80% rich are given by the graphs of Fig. 11.

Values for I.H.P., B.H.P., I.M.E.P., I.T.E., and opt. spark timing are given for a speed of 1500 with mixtures ranging from 70% weak to 80% rich, by the graphs of Fig. 12.

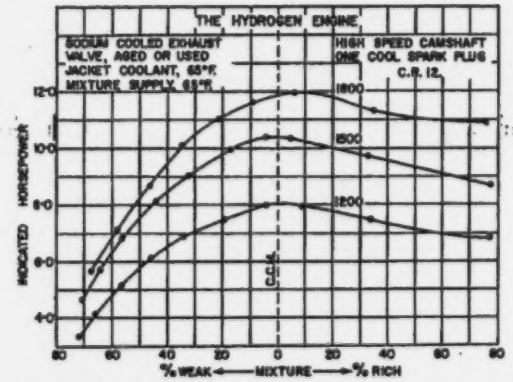

FIG. 11. Power developed at 12:1 C.R. on reducing the concentration of soot derived from pyrolysis of the vapor of excess lubricating oil and thus avoiding nuclear ignition.

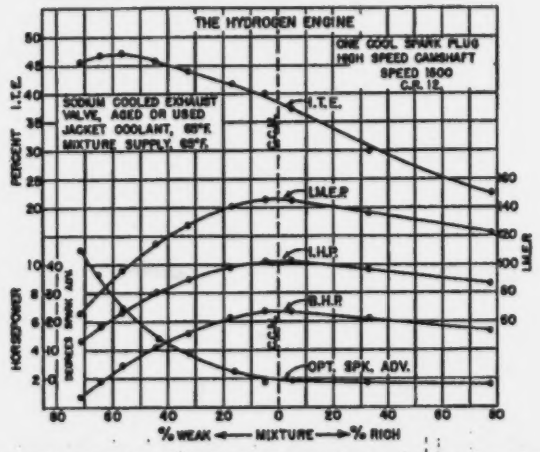

FIG. 12. Performance data obtained in the absence of nuclear ignition when using mixtures 70% weak to 80% rich at 1800 r.p.m. and a C.R. of 12:1.

Performance data obtained when the mixture strength was that required for maximum power and that required for maximum indicated thermal efficiency are of especial interest and are given in Tables VI and VII respectively. Values of opt. spark timing and volumetric efficiency are also given.

It will be seen by references to the tables that a maximum of 146 p.s.i. was obtained for I.M.E.P. when the engine was operated at 1500 r.p.m. and

TABLE VI

MIXTURE STRENGTH FOR MAXIMUM POWER; AGED OR CLEAN EXHAUST VALVE
HIGH SPEED CAMSHAFT, ONE COOL SPARK PLUG, COMPRESSION RATIO 12:1

Speed, r.p.m.	% Vol. eff.	Spark timing	I.H.P.	I.M.E.P.	I.T.E.%
1800	85.4	1° retard	11.9	140	37
1500	89	1° retard	10.3	146	37
1200	87.3	2° retard	8.0	141	36

TABLE VII

MIXTURE STRENGTH FOR MAXIMUM INDICATED THERMAL EFFICIENCY;
AGED OR CLEAN EXHAUST VALVE
HIGH SPEED CAMSHAFT, ONE COOL SPARK PLUG, COMPRESSION RATIO 12:1

Speed, r.p.m.	% Vol. eff.	Spark timing	I.H.P.	I.M.E.P.	I.T.E.%
1800	83.7	25° adv.	7.6	90	47
1500	91.5	25° adv.	6.9	96	47
1200	91	27° adv.	5.3	91	44

that a maximum of 47% was obtained for I.T.E. when the engine was operated at 1800 r.p.m. Values of 47½% were not uncommon but are not shown on the relevant graph of Fig. 12.

Lubricating oil always passed the piston at an abnormal rate when the C.R. was raised to 12. There was therefore always an appreciable concentration of lubricating oil vapor in the compressed hydrogen–air mixture. The pyrolysis of this vapor produced the finely divided carbon which remained in part as soot on the piston crown and required removal by the method described in order to avoid preignition. In these circumstances the difference in the igniting effect due to the exhaust valve being aged or initially clean was masked by the nuclear igniting effect.

The procedure adopted to obtain performance data with a hydrogen–air mixture at a C.R. of 12 was made necessary by the particular design of the C.F.R. cylinder and piston. It could therefore be changed in a manner such that experiments could be carried out at compression ratios higher than 12:1. Thus we have, by limiting the time during which oil passed the piston, been able to operate for a short period at a C.R. of 16:1 with a maximum power mixture.

DISCUSSION

Hydrogen either free or in combination with carbon is a constituent of the gases or liquids commonly used as engine fuels. The characteristics of the combustion of hydrogen only should therefore be of fundamental significance. It seems however to have long been accepted that hydrogen cannot be used as the sole fuel, because of the occurrence of premature ignition, in the operating conditions required to obtain optimum values for power output and the corresponding thermal efficiency.

Lucke (14, 1906) states that "Gases rich in hydrogen *preignite easily* and that approximately one atmosphere should be deducted from the compression pressure allowable with no hydrogen for each 5% of hydrogen present". Tizard (19, p. 22, 1921) states that "Hydrogen *detonates easily* in an internal combustion engine, at quite low compression ratios, but nevertheless it has a high ignition temperature". Ricardo (16, pp. 334–337, 1922), with the E35 engine operated at 1500 r.p.m., found that it was possible to use a nearly correct hydrogen–air mixture at a compression ratio of 5.45:1, but "if an attempt was made to use a rich mixture, violent *preignition* occurred, accompanied by firing back into the carburetor, which rendered further running impossible. Even with the compression ratio lowered to 3.8:1, the same thing occurred". Burstall (2, 1927) operating another E35 engine, at 1000 r.p.m. and compression ratios of 5 and 7:1, found that "The experimental range (of mixture strength) which can be used with hydrogen is strictly limited by its readiness to *detonate*, both at high compression ratios and with rich mixtures, and even more by its tendency to backfire with mixtures richer than 20% weak at a compression ratio of 5:1". Premature ignition, described as *detonation*, was obtained by Egerton, Smith, and Ubbelohde when they were using an ethyl knock testing engine (5, 1935). The effect was attributed at the time to nitrogen peroxide formed from the nitrogen of the air, but some years later to *preignition* (4, p. 917, 1949).

Downs, Walsh, and Wheeler (3, p. 517, 1951), as a result of experiments with hydrogen as the fuel for a Ricardo E6 engine, state that "In most cases, owing to the *extreme ease with which it ignites*, a mixture richer than about 25 to 30% weaker than chemically correct cannot be used. If the attempt is made to run with a richer mixture, *self-ignition* occurs so early in the compression stroke that the mixture is eventually ignited in the induction manifold". The statement that hydrogen–air mixtures "ignite with extreme ease" cannot be accepted as fact. Reference was made to the finding of King, Wallace, and Mahapatra that, by keeping the combustion chamber as clean as possible, the engine could be operated over the whole mixture range without backfiring (12). It was not mentioned that this occurred at a compression ratio of 10:1 and a speed of 900 r.p.m. The reference is also misleading in that it should have been to fluffy carbon that accumulated in an initially clean combustion chamber as described on page 269 of reference (12). Moreover it was not mentioned that preignition and backfiring occurred when charcoal dust was added to the mixture supplied to the engine. Although Ricardo's early statement regarding the impossibility of using rich mixtures is echoed, they describe the premature ignition as "*self-ignition*" instead of by the term *preignition* used by Ricardo. Self-ignition was treated as detonation and attributed to a chain reaction mechanism to be described in a subsequent publication.

Anzilotti and associates (1, 1954) describe experiments with a C.F.R. engine operated at 900 r.p.m. with a jacket coolant temperature of 212°F. and an inlet mixture temperature of 100°F. The results obtained were similar to those of Downs, Walsh, and Wheeler (3) in that, when the mixture strength required for maximum power was used, the highest compression ratio usable without knock was approximately 8:1. It is stated that the "knock" was similar to that obtained with paraffinic fuels and was attributed to the chain reaction mechanism devised by Lewis and Von Elbe to explain the autoignition of *hydrogen–oxygen* mixtures. In our preliminary experiments also carried out with a similar engine and operating conditions but with a combustion chamber initially clean, the knock limited compression ratio was 10:1 when a nearly correct mixture was used (see Fig. 1, this Part) and it was shown by subsequent experiments described in Section I to have been due at 900 r.p.m. to the ceramic core of the spark plug having attained an igniting temperature.

Livengood and Leary (13) obtained what appeared to be autoignition of a correct hydrogen–air mixture when using the compression ignition machine developed by C. F. Taylor and associates (18). The compression ratio was 12:1 and after nearly adiabatic compression the mixture was held against the thick plate glass window which formed the cylinder head until ignition occurred after a few milliseconds. The window was used for photographic recording of the process of ignition and therefore was not cooled. In view of the experiments described in Section III in which a mixture 33% weak was ignited by the surface of the ceramic core of a spark plug at a compression ratio of 10:1, it may safely be assumed that the ignition observed by Livengood and Leary occurred because a layer of molecules on the surface of the uncooled plate glass window attained the required temperature. Thus it was observed by them that "all mixtures give off a bright yellow light during autoignition. When specimen inflammations were examined with a spectrograph, the presence of a strong sodium-D line was revealed in each instance". Efforts were made to find and eliminate the source of the sodium but apparently it was not realized that it could be provided by the plate glass. In spite of their efforts, "all fuels including hydrogen, continued to emit the characteristic yellow light".

The experiments described in this Part show clearly that optimum performance in terms of power and economy is limited only by preignition arising from the temperature attained by the ceramic core of the spark plug or by the exhaust valve or from nuclei formed by pyrolysis of lubricating oil vapor. It was shown by indicator diagrams that detonation, defined as auto or self ignition, did not occur in the absence of nuclei of ignition.

On reducing the magnitude of the igniting effects mentioned it became possible to operate the engine at speeds rising to 1800 r.p.m., with the compression ratio fixed at 12:1. Values of 146 p.s.i. for I.M.E.P. and of 37% for I.T.E. were obtained when the maximum power mixture strength was used. The values obtained with a mixture 55% weak were 90 p.s.i. for I.M.E.P. and 47% for I.T.E. These values exceed those recorded in the literature of the subject, by a wide margin.

ACKNOWLEDGMENTS

The experiments described in this Part were carried out in the Department of Mechanical Engineering, University of Toronto, with the co-operation of

Professor E. A. Allcut, Head of the Department, the assistance of Mr. S. V. Hayes, Scientific Officer Defence Research Board, and that of Joseph Thurner, Technician. Acknowledgment is also made of the assistance with preliminary experiments given by Professor Bernard D. Wood, Department of Mechanical Engineering, University of Manitoba.

The Consumers Gas Company, Toronto, contributed to the experimental work by providing facilities under the direction of Mr. J. Alex Morrison for the calibration of hydrogen metering orifices; the Champion Spark Plug Company, by supplying spark plugs with thermocouples in the central electrodes; The Eaton Manufacturing Company, Detroit, by supplying a silchrome valve with the stem drilled for leads to a thermocouple in the head.

The Authors are indebted to the Chairman of the Defence Research Board for permission to publish this paper.

REFERENCES

1. Anzilotti, W. F., Rogers, J. D., Scott, G. W., and Tomsic, V. J. Ind. Eng. Chem. 46: 1314–1318. 1954.
2. Burstall, A. F. Proc. Inst. Automobile Engrs. 22: 358–392. 1927.
3. Downs, D., Walsh, A. D., and Wheeler, R. W. Trans. Roy. Soc. (London), A, 243: 463–524. 1951.
4. Egerton, A. and Moore, N. W. P. Nature, 163: 917. 1949.
5. Egerton, A., Smith, F. L., and Ubbelohde, A. R. Trans. Roy. Soc. (London) A, 234: 433–521. 1935.
6. Hundere, A. and Bert, J. A. S.A.E. Quart Trans. 546–562. Oct. 1948.
7. King, R. O. Can. J. Research, F, 26: 228–240. 1948.
8. King, R. O., Durand, E. J., and Morrison, J. A. Can. J. Research, F, 27: 435–449. 1949.
9. King, R. O., Durand, E. J., Wood, B. D., and Allan, A. B. Can. J. Research, F, 28: 134–155. 1950.
10. King, R. O., Sandler, S., and Strom, R. Can. J. Technol. 33: 388–407. 1955.
11. King, R. O., Wallace, W. A., and Durand, E. J. Nature, 163: 729. 1949.
12. King, R. O., Wallace, W. A., and Mahapatra, B. Can. J. Research, F, 26: 264–276. 1948.
13. Livengood, J. C. and Leary, W. A. Ind. Eng. Chem. 43: 2797–2806. 1951.
14. Lucke, C. E. Gas engine design. D. Van Nostrand Company, Inc., New York. 1905.
15. Pye, D. R. The internal combustion engine. 2nd ed. Oxford University Press, London. 1937.
16. Ricardo, H. R. Proc. Inst. Automobile Engrs. Vol. 18. 1923–1924.
17. Sanders, J. C., Wilstead, H. D., and Mulcahy, B. A. Natl. Advisory Comm. Aeronaut. Rept. No. 754. 1943.
18. Taylor, C. F., Taylor, E. S., Livengood, J. C., Russell, W. A., and Leary, W. A. S.A.E. Quart. Trans. Apr. 1950.
19. Tizard, H. T. North East Coast Inst. Engrs. & Shipbuilders, May 1921.

APPENDIX

Metering of Hydrogen Supply

Accurate measurement of rate of hydrogen supply to the engine is of prime importance in respect of determinations of thermal efficiency. The novel method used for the experiments was based on the use of two calibrated square edged orifices in thin plates. One was 0.1286 in. and the other 0.0784 in. diameter. The plates were 0.013 in. thick. The orifices were mounted midway in brass tubes 4 in. diameter and 4 ft. long provided with baffles and wire mesh screens for the elimination of pressure pulsations from the induction system of the engine. The double system of hydrogen supply to the engine through

small orifices of different diameters, which could be used singly or in parallel, was such that hydrogen could be supplied at rates required for the experiments while the velocity of flow through a metering orifice was never less than 750 ft. per sec. This feature in conjunction with the means taken to eliminate pressure fluctuations made possible the use of orifice calibrations determined in steady flow conditions.

The orifices, in position in the tube mountings, were calibrated in the Meter Testing Department of the Consumer's Gas Company, Toronto, under the direction of Mr. J. Alex Morrison, Supervisor of the Appliance Laboratory. A special gasometer which had been calibrated by the Ontario Department of Weights and Measures was used. A graph obtained accordingly for the relation between pressure difference and rate of hydrogen flow through the 0.1286 in. diameter orifice as plotted on a logarithmic scale is given by Fig. 13. The values given for rates of hydrogen flow are for a temperature of 60°F. and a pressure of 30 in. Hg.

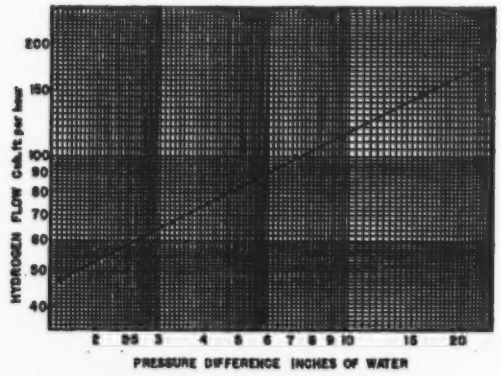

FIG. 13. Calibration graph for orifice 0.1286 in. diameter.

Accuracy of Measurement of Thermal Efficiency

The accuracy of measurement of I.H.P. by the motoring method, which is in general use, is not regarded as better than $\pm\frac{1}{2}$ of 1%. It is considered that the rate of hydrogen consumption was made with an accuracy of $\pm\frac{1}{4}$ of 1%. The values for I.T.E. given in this part are comparable with those obtained by Ricardo (16) and Burstall (2) when they used the motoring method of measuring I.H.P. Values for power and thermal efficiency are not given in more recent publications by others (1, 8).

The Spark Plugs

The spark plugs used for the experiments are illustrated by Fig. 14. Champion C.F.R.-8 is near the top of the commercial heat scale and was used as a

hot variety with a spark gap of 0.025 in. Spark plugs K.L.G. 100 and R2-S, rated at the bottom of a commercial heat scale, were used as cool varieties. The spark gaps of these plugs are not readily adjustable. They were used as supplied with gaps of 0.018 in. approximately. It would be expected according

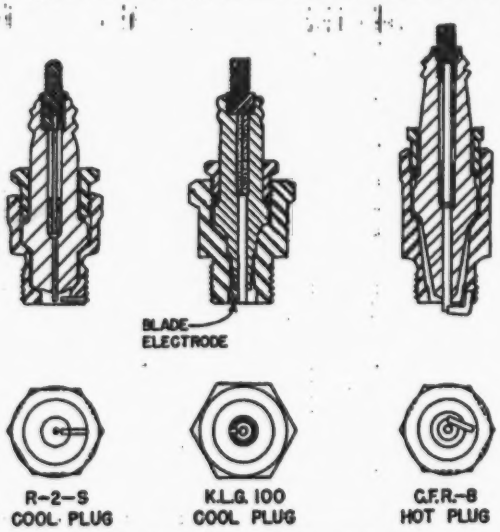

FIG. 14. Spark plugs used for the experiments.

to the designs that the K.L.G. plug would run hotter than the R2-S but it was shown by experiments, Section III, that neither attained the temperature required for the preignition of hydrogen–air mixtures in the conditions of the experiments of this Part.

Valve Timing

The low and high speed camshafts were designed to provide valve timings as tabulated below, according to the C.F.R. handbook. The given values were found to be correct within 1°.

	Low speed camshaft	High speed camshaft
Inlet valve opens	10° after t.d.c.	15° before t.d.c.
Inlet valve closes	34° after b.d.c.	50° after b.d.c.
Exhaust valve opens	40° before b.d.c.	50° before b.d.c.
Exhaust valve closes	15° after t.d.c.	15° after t.d.c.
Valve lift	0.238 in.	0.312 in.
Valve overlap	5°	30°

When the high speed camshaft was used, the exhaust valve with a lift of 0.312 in. was off its cooling seat for 155° of crank revolution. When the low

speed camshaft was used, the exhaust valve with a lift of 0.238 in. was off its cooling seat for 145° of crank revolution.

Exhaust Valves

The types of sodium cooled and uncooled silchrome exhaust valves used for the experiments described in this Part are illustrated by Fig. 15.

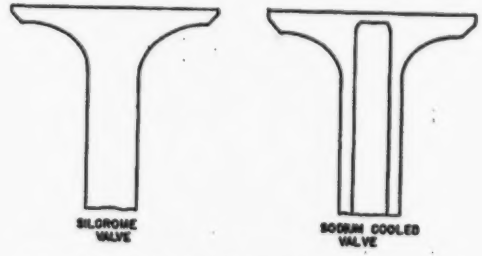

FIG. 15. Types of exhaust valves used for the experiments.

#26094